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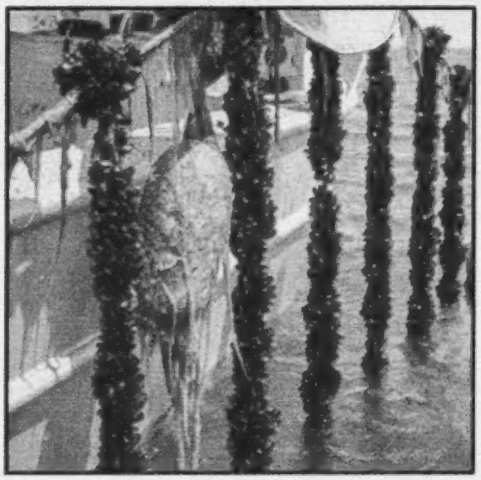
Science Advisory Report 2015/003

Gulf Region

CARRYING CAPACITY FOR SHELLFISH AQUACULTURE WITH REFERENCE TO MUSSEL AQUACULTURE IN MALPEQUE BAY, PRINCE EDWARD ISLAND



Mussel socks suspended to longline (Photo courtesy of A. Ramsay)

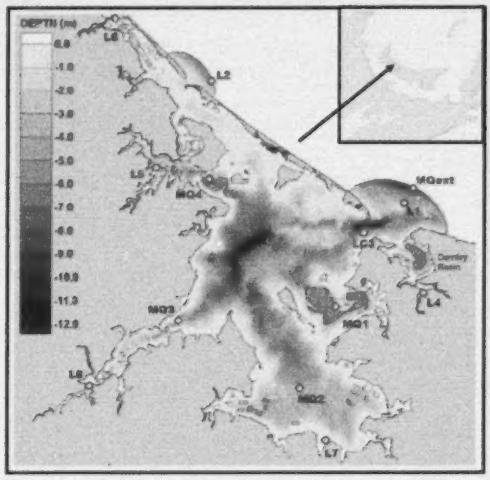


Figure 1. Map of Malpeque Bay (PEI) including bathymetry, current mussel leases (red polygons), sampling stations, and hydrodynamic stations (Filgueira et al. 2014).

Context:

In Prince Edward Island (PEI), shellfish (bivalves comprised of mussel and oyster) aquaculture production occurs in sheltered, generally shallow bays. The productive capacity of a bay for shellfish aquaculture is determined by many factors including the hydrodynamics of the bay and input of nutrients. There is considered to be a limit to the production (biomass) that can be extracted from an area due to competition for the limiting resource which is phytoplankton, the primary trophic level. Requests were made to increase the amount of leases for the production of mussels in Malpeque Bay, PEI. In support of the development of a bay management plan for Malpeque, DFO Gulf Region Aquaculture Management asked for advice on how much expansion could occur without exceeding the carrying capacity of the bay. The question was refined to assess a proposal for an additional 590 ha of suspended mussel leases in Malpeque Bay. This Science Advisory Report is from the regional science peer review meeting of Oct. 8-9, 2014 on the carrying capacity for shellfish aquaculture with reference to mussel aquaculture in Malpeque Bay, PEI. Participants at the meeting were from DFO Science Gulf, Maritimes, Quebec, Pacific and National Headquarters regions, DFO Aquaculture Management Gulf Region, province of PEI, universities, and the shellfish aquaculture industry. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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SUMMARY

- This advice is provided to inform the marine spatial planning process in consideration of a request to increase suspended mussel aquaculture acreage in Malpeque Bay, Prince Edward Island. The analysis is provided relative to the concept of carrying capacity of Malpeque Bay to support current and potential increases in suspended mussel culture.
- Carrying capacity has been defined based on multiple viewpoints (physical, production, ecological, and social). This advisory report addresses mussel aquaculture in the context of production carrying capacity and ecological carrying capacity.
- In this report, production carrying capacity is assessed as the magnitude of aquaculture activity that maintains mussel growth within the range of variation in the current leases.
- Ecological carrying capacity (defined as the magnitude of aquaculture activity that can be supported without leading to unacceptable changes in ecological processes, species, populations, communities, and habitats in the aquatic environment) is partially considered by focusing on phytoplankton dynamics but cannot be fully assessed given that unacceptable changes have yet to be defined. Thresholds for unacceptable changes would be defined by management.
- Production and ecological carrying capacity are typically investigated using mathematical models that integrate complex interactions between aquaculture activities, bivalve physiology, and the environment. Due to the significant influence of local environmental conditions on ecosystem functioning, carrying capacity studies are site specific.
- Estimation of phytoplankton utilization by bivalves has been used to assess production and ecological carrying capacity, given that phytoplankton constitutes the primary step in the planktonic marine food web and is a main food source for bivalves.
- Cultured mussels are presently the dominant filter-feeders in Malpeque Bay.
- The proposed suspended mussel lease expansion in Malpeque Bay of up to 590 ha would increase the leased spatial area coverage from 7% to 10%. The placement scenario for the projected leases used in this assessment could be modified during subsequent steps of the consultation and marine spatial planning process.
- Model predictions of changes in chlorophyll *a* and mussel growth were used to assess the state of production carrying capacity of Malpeque Bay.
- Under current and projected levels of mussel culture and relative to the metrics of production carrying capacity used in this assessment, the production carrying capacity of Malpeque Bay would not be exceeded.
- Considerations of benthic habitat and community effects, dynamics (energy flow and nutrient cycling), and epifauna communities associated with the aquaculture infrastructure are required for a complete ecological carrying capacity assessment. The link between benthic and pelagic components and their interactions, in terms of vicinity versus bay scale effects, requires further work.
- While there are various options for production carrying capacity and ecological carrying capacity indicators, there is much uncertainty with respect to establishing thresholds that are linked to unacceptable biological and/or ecological changes.

INTRODUCTION

Approximately 4,500 ha of estuarine waters in Prince Edward Island (PEI) are leased for mussel aquaculture with an annual production of approximately 20,000 tons. Mussel aquaculture in PEI is carried out using a longline system of suspended polyethylene sleeves. Seed collector ropes are deployed in spring and recovered in early autumn when recruited mussel seed reach approximately 15 - 20 mm in shell length. Seed is stripped from collector ropes and placed into 1.8 m long polypropylene sleeves that hang from 100 to 200 m longlines, positioned 1 m below surface to avoid damage by ice cover during winter. Mussels are typically maintained at densities between 1.10 and 2.07 kg per m^2 cultured area but since only approximately 58% of a lease area is utilized at any given time (Comeau et al. 2008), the effective density of mussels would range between 0.64 and 1.2 kg per m^2 of leased area. Cultured mussels in PEI may attain a harvestable size (shell length > 55 mm) in the fall of their second year (~18 months) although most reach a harvestable size the following spring - summer (~24 months).

In 1999 - 2000, a moratorium on further leasing for mussel aquaculture was initiated in PEI. In 2007, a request was made to review the moratorium and Malpeque Bay was identified as one of the areas in PEI for potential mussel aquaculture expansion. The total area of the Malpeque Bay system is 19,640 ha of which 1,431 ha (~7%) are currently leased for bivalve aquaculture (769 ha for mussels and 662 ha for oysters). In 2013, DFO identified the need to develop a detailed spatial plan to accommodate the potential increase in aquaculture acreage in Malpeque Bay. The exact locations in the bay of possible future mussel aquaculture leases are still under consideration. One of the considerations in the spatial planning and decision making process by DFO Aquaculture Management is the question of how much expansion could occur without exceeding the carrying capacity of the bay.

In shellfish aquaculture, the concept of carrying capacity has traditionally been regarded in the context of maximizing stocking biomass and profitability at the farm scale. Over the past decades the concept of carrying capacity and its level of complexity have changed. To address the request for advice from DFO Aquaculture Management on how much expansion could occur without exceeding the carrying capacity of the bay, the following questions were considered:

- How to define production and ecological carrying capacity.
- How to estimate production and ecological carrying capacity.
- What are the indicators that could be used to establish the carrying capacity of a bay, and to determine if the carrying capacity has been exceeded?
- Specific to Malpeque Bay, what is the current level of cultivated mussel biomass, would increasing acreage by 590 ha impact the production of existing mussel farms, and are there any indications that the production or ecological capacity is already attained for some regions of Malpeque?

ASSESSMENT

Bivalve species, indigenous and cultivated, are an integral component of marine ecosystems and, coupled with hydrodynamic processes, can have both direct and indirect effects on various other biotic communities (DFO 2006). A science review of habitat risks associated with bivalve aquaculture in the marine environment concluded that the type and intensity (scale) of the culture activities, the seasonal and physical characteristics of the aquaculture site, and the state of the marine habitat being assessed, in relation to other anthropogenic activities, are all determining factors in terms of habitat sensitivity to shellfish aquaculture (DFO 2006). All these considerations are encompassed in the concept of carrying capacity.

Definitions of carrying capacity

Carrying capacity can be defined at differing component and objectives scales (McKindsey et al. 2006; Gibbs 2007; Byron and Costa-Pierce 2013; McKindsey 2013; Filgueira et al. 2015a).

- Physical carrying capacity: the area that is geographically available and physically / chemically adequate for the aquaculture activity. It is useful to quantify the potential area available for aquaculture but it provides little information for management and regulation.
- Production carrying capacity: the magnitude of aquaculture activity in a given area corresponding to maximum biomass production, or maximum marketable production (considering growth rates and cost-benefits), or the trophic web being theoretically reduced to the nutrient-phytoplankton-bivalve loop.
- Ecological carrying capacity: the magnitude of aquaculture activity in a given area that can be supported without leading to unacceptable changes in ecological processes, species, populations, communities, and habitats in the aquatic environment. It should, in principle, consider the whole ecosystem and the interactions with all the activities involved in the aquaculture process. Thresholds for unacceptable outcomes need to be defined by management.
- Social carrying capacity: the aquaculture activity in a given area that can be developed without adverse social impacts. The additional dimension(s) in social carrying capacity are those that relate to socio-economic and cultural objectives.

For the purpose of this assessment, production carrying capacity is defined as the magnitude of aquaculture activity that maintains mussel growth within the range of variation in the current leases.

How to estimate production and ecological carrying capacity

The methodological approaches for assessing carrying capacity range from indices of processes, to farm models, spatial models, and food web models. These models utilize core biogeochemical (nutrient-seston-bivalve interactions) and hydrodynamic (water exchange coefficients) equations of varying dimensions and complexity (Fig. 2). Each class of models has advantages and disadvantages and differing data requirements.

Indices based on the comparison of key oceanographic and biological processes have been used as proxies for the carrying capacity of bivalve aquaculture sites. The common rationale of these indices is in comparing the energy demand of bivalve populations (based on filtration rates) and the ecosystem's capacity to replenish these resources, which depends on advection and local production. Dame and Prins (1998) proposed indices of phytoplankton depletion, i.e. reduction, based on the ratios among water residence time, primary production time and bivalve clearance time. These provide a relatively simple way to assess the influence of bivalves on embayment-scale ecosystem processes, and specifically phytoplankton dynamics (Grant and Filgueira 2011).

Farm-scale models restrict the model domain to the extent of the farm and their outputs are limited to assessing production carrying capacity with the focus on the bivalve-phytoplankton interaction, since phytoplankton depletion is most obvious at this local scale (Grant et al. 2007; Cranford et al. 2014). At the farm scale, phytoplankton dynamics are dominated by physical (advection) rather than biogeochemical (primary productivity) processes (Duarte et al. 2005). Farm-scale models usually include a hydrodynamic model to describe water circulation through the farm and a bioenergetic model to describe bivalve filtration and growth. When the model is focused only on phytoplankton depletion, a simple flow equation based on average clearance

rate of the bivalves could be used to describe the phytoplankton-bivalve interaction but this form lacks the capability to predict bivalve growth. Farm models are generally considered useful for optimizing lease geometry and configuration.

Spatially-explicit models are particularly desirable due to their more accurate description of complex hydrography, the consideration of interactions between and among farms, and straightforward applications of outcomes to marine spatial planning processes. In box spatial models, the domain is divided into few large areas that are considered homogeneous. In fully-spatial models, a grid with hundreds or thousands of polygons is defined to represent the model domain. Nevertheless, spatially-explicit models are complex and require more data for calibration and as a result can increase scientific uncertainty of the outcomes. The output of box models may be as uncertain as more complex models but may not appear so because variability is simply averaged and unaccounted for in outcomes.

Mass-balance food web models have also been used to explore the influence of bivalve aquaculture on food web dynamics. The main advantage of food web modelling is that it allows the study of many species and trophic levels at the same time, a task that is very difficult to achieve with any of the models previously described. The drawback is that they use a largely top-down mass-balance approach and poorly represent bottom-up effects, which are critical in bivalve aquaculture sites due to the impact of cultured biomass on nutrients and detritus (McKindsey 2013). Studies using such models have concluded that production carrying capacity is higher than ecological carrying capacity.

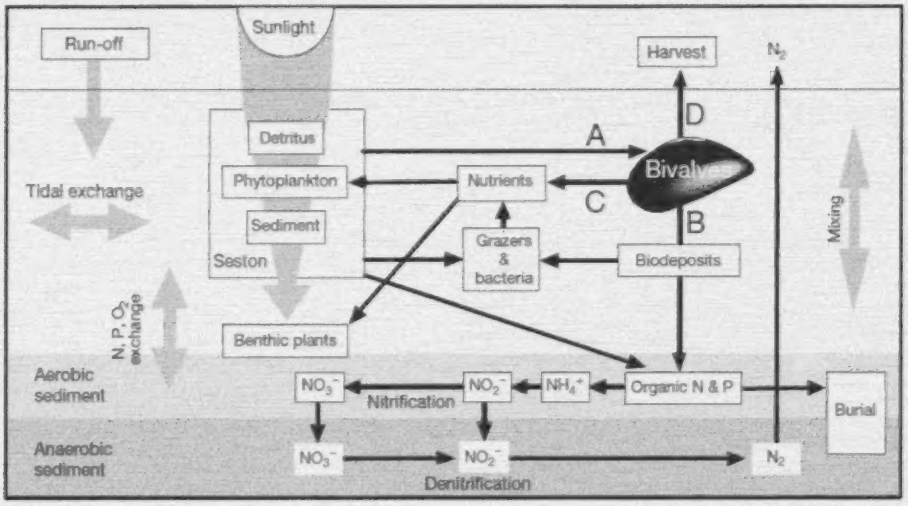

Figure 2. Conceptual diagram of bivalve aquaculture interactions in coastal ecosystems related to: (A) the removal of suspended particulate matter (seston) during filter feeding; (B) the biodeposition of undigested organic matter in faeces and pseudofaeces; (C) the excretion of ammonia nitrogen; and (D) the removal of materials (nutrients) in the bivalve harvest (from Cranford et al. 2006). The hydrodynamic component includes the vectors of run-off, tidal exchange, and mixing. The biogeochemical component includes all the other pathways in the diagram. The pelagic component considered in this review relates to process arrows A and C.

Potential indicators of carrying capacity and its exceedance

Indicators are used to help describe the status of ecosystem components and serve as a way to assess and quantify changes, progress, and improvements towards sustainable industry development (Cranford et al. 2012). No one universal set of indicators is applicable in all cases,

and no single indicator can account for the whole ecosystem. However, a small set of well-chosen and highly relevant indicators tends to be the choice of most applications. Potential ecological indicators specific to bivalve culture are summarized in Cranford et al. (2006, 2012). These indicators specifically address ecosystem components and processes from the farm footprint to far-field effects (coastal ecosystem scale). The set of indicators are related to the following three categories:

- the state of the benthic habitat and associated community relevant to assessing the effects of increased organic matter deposition by bivalve aquaculture,
- the intensity of pelagic alterations and impacts from the activities of cultured bivalves (including seston and phytoplankton depletion), and
- the changes in bivalve performance as an indication of environmental feedbacks on the culture (whether bivalve aquaculture is affecting the system to a greater extent than can be absorbed by natural processes, including food depletion).

The benthic and pelagic indicators address ecological status related to both production and ecological carrying capacity, while the bivalve performance indicators are largely used for assessing the status of production carrying capacity (Cranford et al. 2012). Food depletion can also be used as one metric for assessing ecological carrying capacity, given that phytoplankton constitutes the primary step in plankton-based marine food webs.

Most carrying capacity models have focused on the dynamics of phytoplankton or organic seston and their interaction with bivalves, with a focus on the extent to which bivalves utilize these food resources (related to ecological carrying capacity) and may become susceptible to reduced growth (related to production carrying capacity). The threshold for unacceptable growth effects needs to be defined by management.

Grant and Filgueira (2011) proposed thresholds based on the premise that cultivated bivalves should not be allowed to graze primary producers down to a level outside their natural variability range. In other words, these thresholds consider whether aquaculture signals can be detected against the ecosystem background noise (Ferreira et al. 2013).

The main shortcoming of any assessment of carrying capacity is that the criterion or threshold for whether carrying capacity has been reached is typically subjective.

The case of Malpeque Bay

The Malpeque Bay system is located on the North shore of PEI. It is a large (19,640 ha) and shallow embayment composed of several basins (Fig. 3). An intricate river system discharges into Malpeque at several different points. The system is open to the Gulf of St. Lawrence through multiple connections.

Current level of cultivated mussel production

Currently, most of the mussel aquaculture activity (blue polygons in Fig. 3) is located in the Northeast area of the bay in two sub-basins, Marchwater and Darnley Basin, that are partially isolated from the main water body. The connectivity of Marchwater to the main water body is restricted by a series of islands and shallow areas (Fig. 3). Darnley Basin is located close to the mouth of the bay and connected to the main system through a narrow channel (Fig. 3). The other areas for mussel aquaculture are spread along the shore within the bay in areas more open to circulation than Darnley Basin and Marchwater.

Cultured mussel is presently the dominant filter-feeder in Malpeque Bay. Estimates of cultivated mussel biomass are subject to uncertainty due to husbandry variables such as seeding

densities, fall offs, harvesting, and lease use. Based on leased area and husbandry information available, the cultured mussel biomass in Malpeque Bay is estimated to be between 5,120 and 9,600 t and the annual reported harvest of mussel averages 3,430 t. By comparison, suspension cultured oyster biomass is about 400 t. Bottom oyster biomass is undocumented, rendering difficult a more comprehensive comparison between mussels and oysters. The annual port landings of all oysters (cultured and wild confounded) averaged 169 t over the 1984 to 2011 period with the bulk of the oyster landings reported from the northwestern part of the bay, close to the open boundary with the Gulf of St. Lawrence and the Grand River area.

Assessment of impact on existing mussel farms of expanding acreage of mussel culture by 590 ha

Proposed lease expansion in Malpeque Bay of 590 ha would increase the leased spatial area coverage from 7% to 10%. The scenario examined in this study places the new leases in the central part of the system, south of Marchwater, and on the western shore (Fig. 3). These potential new leases are all at least 1500 feet (~457 m) from the shoreline and in waters at least 15 feet (~4.6 m) deep. The exact locations in the bay at which possible future mussel aquaculture leases could be added are still under consideration. The scenario examined in this review could be modified during subsequent steps of the consultation process. While the conclusions of the present assessment are specific to the scenario explored, it serves as an example of a science-based approach for managing mussel aquaculture expansion based on model-based predictions of the spatial scale and magnitude of mussel growth and phytoplankton dynamics.

Three different models, using a common hydrodynamic component were used to assess connectivity, organic seston, and phytoplankton.

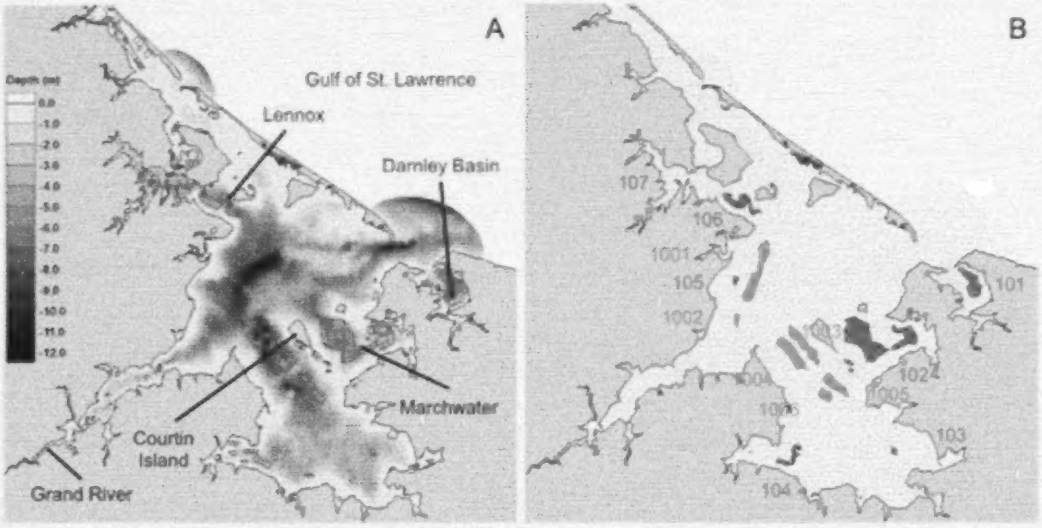

Figure 3. Panel A. Water depth, current and new mussel leases (blue and red polygons respectively), as well as oyster leases (dark red). Panel B. Triangular mesh used in the modelling exercises and current and future mussel cultivation areas, blue and red, respectively. Cultivation areas codes are used to facilitate the summarization of the results.

Connectivity

A two-dimensional, vertically-averaged finite element hydrodynamic model was developed for Malpeque Bay (Filgueira et al. 2014). This model was used to reproduce water circulation within Malpeque Bay in response to tidal and river forcing. Transfer time and transfer rate were calculated using the outcomes of the hydrodynamic model to describe the spatial connectivity of the system. The connectivities were calculated using a probabilistic analysis.

The current leases are not strongly inter-connected whereas the projected leases are strongly inter-connected (Fig. 4). The connectivity from projected leases to current leases is weak, however, the connectivity from current leases to projected leases is stronger, with the current leased areas connected to some degree to all projected leased areas (Fig. 4).

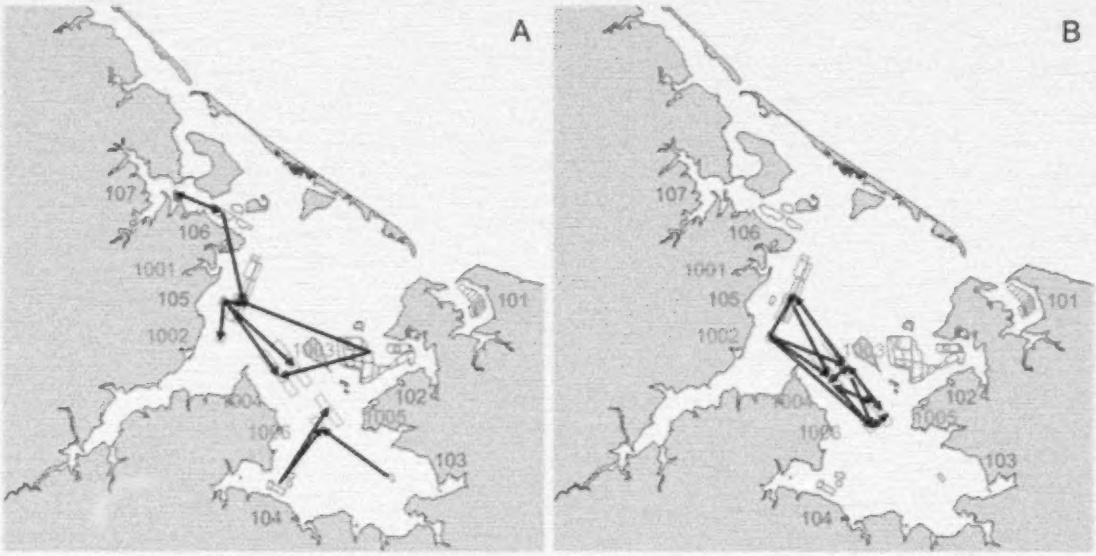

Figure 4. Summary of the most important inter-lease connectivities from current to other leases (A) and from projected leases to other leases (B).

Organic seston

Modelled tracer concentrations were used to simulate seston within the bay. The transport and concentration of a numerical tracer representing sestonic bivalve food was modelled based on water velocity (direction and speed), phytoplankton primary production rate, and the bivalve population clearance rate (Filgueira et al. 2015b). Other sources of seston, such as resuspension and inputs from terrestrial sources, were not included in the model. The outcomes of the model are interpreted in relative rather than absolute terms, with the aim of identifying the most sensitive areas of the bay to increased bivalve aquaculture production. Two scenarios were simulated, one with the current mussel leases only and a second one with the current plus the potential projected leases. In Figure 5, the predicted tracer concentration of the projected scenario was subtracted from the predictions of tracer concentration based on current leases only. The figure highlights the areas that potentially would have the greatest predicted reductions in tracer concentrations resulting from the projected leases.

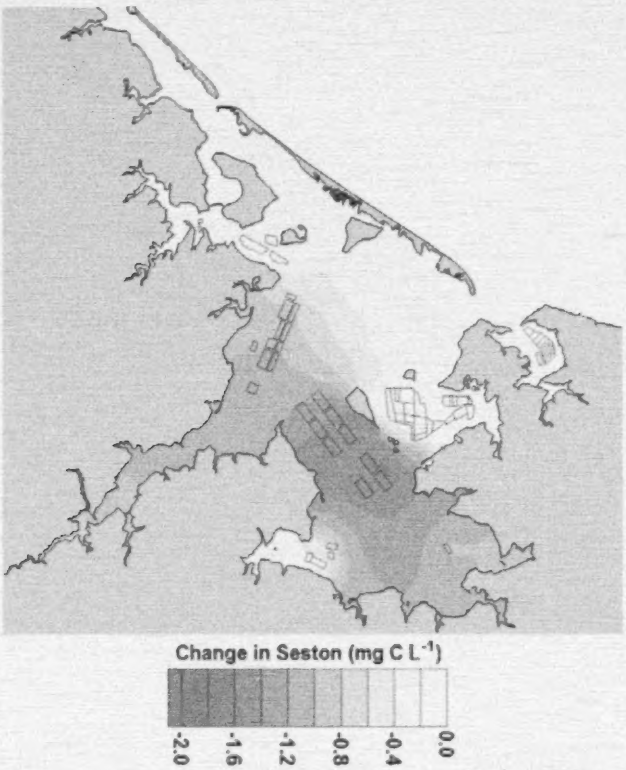

Figure 5. Net change in tracer (seston) concentration resulting from the addition and placement of the projected leases relative to the tracer concentrations with only the current leases.

The predicted net change in tracer concentration resulting from the projected leases was essentially zero for the current mussel leases in Darnley Basin and the inner parts of Lennox (northwest) and Marchwater. However, the projected leases reduced tracer concentrations by a small extent over much of the Marchwater outer region, and in current leases located in the southern part of Malpeque (Fig. 5).

Phytoplankton

Phytoplankton concentration was calculated using chlorophyll as a proxy for phytoplankton abundance. To generate these values, the hydrodynamic model was coupled to a biogeochemical model that included sub-models for phytoplankton, nutrients, detritus, mussels and associated tunicates (Filgueira et al. 2015b).

At the bay-scale, the current aquaculture scenario reduced predicted chlorophyll *a* by 0.3 µg l^{-1} compared to a scenario without aquaculture. In comparison, the current scenario plus full projected lease scenario predicted reductions of chlorophyll *a* by 0.6 µg l^{-1}. This reduction is within the range of measured natural variation of chlorophyll concentration in the current situation of the bay (average chlorophyll concentration and standard deviation; 3.0±1.1 µg l^{-1}). A representation of the net change in phytoplankton concentration resulting from the projected lease scenario relative to the scenario with current leases only is presented in Figure 6. The projected leases would reduce phytoplankton concentration over the entire system with the most substantial reduction south of Courtin Island and extend into the Marchwater area. This predicted reduction in phytoplankton concentration would therefore amplify the reduction associated with the current leases in Marchwater.

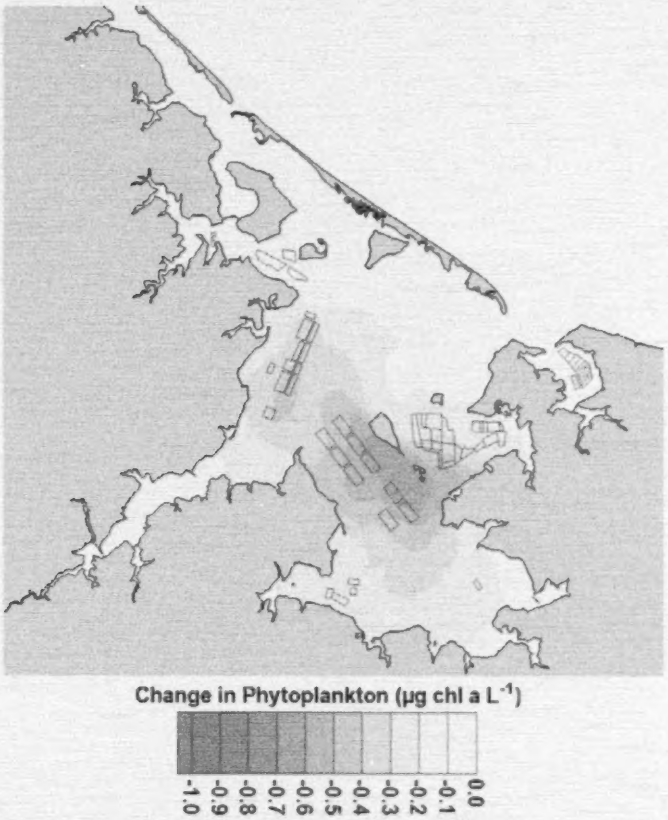

Figure 6. Net change in phytoplankton concentration for the projected leases plus current lease scenario relative to only the current leases.

The ecosystem model predicts that the reduction in chlorophyll due to the projected leases would reduce mussel growth by 8% (± 2%) in the Marchwater area, by 6% within the small lease on the western shore, and by less than 1% for Darnley Basin.

Are there any indications that the production or ecological capacity is already attained for some regions of Malpeque

Based on the full spatial model, the situation within Malpeque Bay is quite diverse. The filtration pressure by current mussel leases causes a reduction in seston in Darnley Basin and Marchwater whereas the inner part of the system is homogeneously enriched in organic seston. There is a predicted increase of phytoplankton inside the bay resulting from nutrient inputs from freshwater. Only the bivalve culture areas located in the northeast part of the bay reduced chlorophyll levels.

Predicted net changes in organic seston and phytoplankton associated with the placement of the projected leases suggest bay-scale effects would occur but of small magnitude. There would be a small predicted reduction in chlorophyll *a* (0.6 µg l^{-1}) in the bay which presently has high chlorophyll levels (measured average chlorophyll concentration and standard deviation; 3.0±1.1 µg l^{-1}) attributed to high nutrient loading from freshwater inputs. Current and projected aquaculture lease placements would not deplete phytoplankton populations below the boundary conditions measured at the Gulf of St. Lawrence (1.4 ± 1.0 µg l^{-1}). The connectivity analysis indicates that the placement of the projected leases in the scenario would not reduce the

availability of organic seston and phytoplankton within the current lease areas. Based on the ecosystem model, the predicted reduction in chlorophyll will result in a reduction in mussel growth of 8%, a value which is within the 20% variation of mussel growth regularly measured in mussel culture in this area (Filgueira et al. 2013).

There is no indication that under current and projected levels of mussel culture and relative to the metrics of production carrying capacity used (changes in chlorophyll, changes in growth rate of cultured mussels) that the production carrying capacity of Malpeque Bay would be exceeded.

Sources of Uncertainty

Benthic effects and dynamics and epifauna communities associated with the aquaculture infrastructure are required in an ecological carrying capacity assessment but these were not fully considered in the modelling assessment of Malpeque Bay. The link between benthic and pelagic components and their interactions, in terms of vicinity versus bay scale effects can be an important factor in PEI embayments (Cranford et al. 2007) and incorporation of these interactions in an ecological carrying capacity assessment requires further work.

Advising on thresholds is complicated by the fact that an ecosystem's response to a disturbance may be an increase in variability, such that no change is observed in the mean values (Cranford et al. 2012). Such issues have led to considering thresholds of potential concern (TPC), which are a set of operational goals along a continuum of change for selected environmental indicators. TPC values can change when new ecological information is available, allowing managers to distinguish normal 'background' variability from a significant change (see Cranford et al. 2012).

The inclusion of additional processes affecting phytoplankton dynamics in an attempt to bolster ecological realism increases model complexity but imperfect knowledge of ecological relationships, parameters and forcing functions and modelling assumptions may increase scientific uncertainty. This implies that modelling should restrict its focus to the most relevant components and critical dynamics, which must be defined based on the management question to be addressed, available data (including forcing conditions), the important system features, and the appropriate scales. Ultimately, model validation against direct observations is critical to determining the appropriate level of model simplification and the acceptable degree of uncertainty.

A sensitivity test was performed for several parameters of the model. Analyses indicated that seston concentration was less sensitive to changes in the parameters than nutrients and chlorophyll concentration. Model outcomes are not very sensitive to changes in the parameters of the seston and mussel submodels that were evaluated. The primary production rate was the parameter that most affected model outcomes, causing a change in phytoplankton concentration of +19.6% and -17.0% when the rate was changed +10% and -10%, respectively.

The information for constructing an ecosystem model based on a nutrient-phytoplankton-zooplankton dynamics with the addition of mussel and seston submodels was available from multiple data sources for Malpeque Bay. The ecosystem model showed partial disagreement between field observations and predicted values, mainly related to an overestimation of simulated nutrient concentrations. The potential causes of this overestimation are discussed in Filgueira et al. (2014). These include:

- uncertain knowledge of the magnitude of inputs of nutrients from rivers,
- use of parameter values and functions for remineralization, primary productivity and phytoplankton mortality borrowed from neighbouring PEI bays but identified as very sensitive to model outcomes,

- the fact that phytoplankton productivity in the model is assumed to be limited by nitrogen, which is possibly not the case for Malpeque Bay, and
- the lack of other primary producers such as *Ulva* sp. in the model, which could play an important role in productivity and nutrient dynamics in PEI embayments.

The hydrodynamic model was run under restricted forcing conditions that included only the tidal and river discharge components. The effect of winds and waves on the circulation was excluded. Since this high frequency forcing was not accounted for, it is likely that the model underestimated mixing within the bay. However, this shortcoming has no implications for the 'connectivity' and 'seston' analyses, which are probabilistic and relative analyses that aim to identify the strongest spatial connections and most sensitive areas to seston concentration reductions. Regarding phytoplankton dynamics, the underestimation of mixing yields a worst-case scenario for local reduction of phytoplankton concentration and consequently for mussel growth.

The effects of projected farm infrastructure on hydrodynamics (drag) were not included. Data to parameterize these effects are available from literature, although their inclusion would require further sampling to perform a highly detailed spatial calibration of the model. The expectation is that the residence time and other oceanographic characteristics would be locally affected but less so on a baywide scale.

The present study cannot provide a definitive assessment of ecological carrying capacity in Malpeque Bay. Further research is needed to refine inputs and reduce model uncertainties.

CONCLUSIONS AND ADVICE

Impacts related to bivalve aquaculture may occur in both benthic and pelagic environments. Impacts on the environment may trigger larger ecosystem effects, potentially affecting phytoplankton populations and concomitantly higher trophic levels that depend on phytoplankton production. Two carrying capacity components, production and ecological, are typically investigated using mathematical models that integrate complex interactions between aquaculture and the environment. Due to the significant influence of local environmental conditions on ecosystem functioning, carrying capacity studies are site specific.

Indices, farm models, spatial models, and food web models are useful tools for exploring carrying capacity and each has advantages and disadvantages. Spatially-explicit models are particularly desirable due to their more accurate description of complex hydrography and straightforward applications of outcomes to marine spatial planning processes. Nevertheless, spatially-explicit models demand a high level of complexity, which in turn can increase scientific uncertainty of the outcomes. Accordingly, the modelling approach as well as spatial scale and resolution of the model must be adjusted to the goals of the study.

The main challenge in the estimation of ecological carrying capacity is the definition of acceptable / unacceptable ecological impacts. Identifying tipping points of ecological resilience is critical for identifying thresholds and advancing the application of ecological carrying capacity. Grant and Filgueira (2011) have defined thresholds based on the premise that cultivated bivalves should not be allowed to graze primary producers down to a level outside their natural variability range.

The main concern relative to carrying capacity in using the model results for advice is related to the uncertainties. In particular, if the uncertainties lead to an underestimation of the predicted chlorophyll consumption by cultured suspension feeders (bivalves and associated tunicates) this may result in an underestimation of the consequences of projected leases on production of mussels in current leases and on other components of the ecosystem. This concern is in part

alleviated by the fact that the addition of land-sourced nutrients to Malpeque Bay is the dominant input of nutrients to the system, as estimated by phytoplankton primary production. Measured chlorophyll concentrations in Malpeque Bay are on average 2 to 3 times higher than those of the boundary waters of the Gulf of St. Lawrence. Furthermore, nutrient enrichment effects are most likely exacerbated by the fact that wild populations of filter feeders, such as oysters, are well below historical levels. Cultured bivalve filtration as well as uptake by benthic macrophytes and by nuisance macroalgae are probably the only reasons that chlorophyll levels in Malpeque Bay are not even higher.

Model outputs with the placement scenario of the projected leases suggest that changes in mussel growth will be small and within the variation in realized growth rates in this area. The changes in chlorophyll and in mussel growth predicted by the model associated with the placement of the projected new leases must be considered in the context of their natural variation. A change in chlorophyll levels of 0.6 $\mu g\ l^{-1}$ is not of concern in a bay which is susceptible to eutrophication due to river nutrient inputs; nine of its tributaries had reported anoxic events between 2008 and 2012 (Bugden et al. 2014). Similarly, a change in mussel growth of 8% is well within the variation of mussel growth regularly observed in mussel culture in this area. Although there are uncertainties associated with model predictions, the model predicts mussel growth rates consistent with other estuaries in PEI.

Under current and projected levels of mussel culture and relative to the metrics of production carrying capacity used in this assessment (changes in chlorophyll and changes in growth rate of cultured mussels), the production carrying capacity of Malpeque Bay would not be exceeded.

OTHER CONSIDERATIONS

One of the challenges in the assessment of states of shellfish aquaculture relative to ecological carrying capacity is the absence of a definition of acceptable / unacceptable ecological impacts. These outcomes, in terms of objectives (acceptable or desirable) and impacts (unacceptable) must be informed by management. Some impacts or unacceptable outcomes to the ecosystem and their benchmarks could be informed by government legislation (Cranford et al, 2012) such as the Species at Risk Act, the Fisheries Act, and the Oceans Act as well as policies for Fisheries Protection and the Sustainable Fisheries Framework. In practice, assessing the extent of interactions between bivalve culture activities and various components of the ecosystem at multiple trophic levels will be challenging. Such assessments and advice will require the development of food web models that can link trophic level interactions and therefore make predictions on species specific responses (growth, survival, recruitment) relative to variations in the magnitude of the aquaculture activities (Byron et al. 2011a, 2011b).

SOURCES OF INFORMATION

This Science Advisory Report is from the October 8-9, 2014 Gulf Region science peer review meeting of Carrying capacity for shellfish aquaculture with reference to mussel aquaculture in Malpeque Bay, Prince Edward Island. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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